POI RIVER SEDIMENT CONTROL POST - EARTHQUAKE

Elieser Palantik[1], Joko Nugroho[2], Arie S Moerwanto[1], Edy Anto Soentoro[2] and Radia Zulfikar[1]

[1] Ministry of Public Works and Housing, Jakarta, Indonesia
[2] Water Resources Engineering Research Group, Faculty of Civil and Environmental Engineering, ITB, Bandung, Indonesia

Abstract.The earthquake of magnitude 7.4 that occurred on September 28, 2018 caused a landslide in Poi Village. Post the earthquake, there were two flood events accompanied by debris flows, on June 29, 2019 and December 8, 2019. In order to anticipate the recurrence of debris flow, the Ministry of Public Works and Housing (PUPR) in 2020 has built a sabo dam and five consolidation dams. This research is aimed to study the impact of the sabo dam built to control debris flows in Poi River. Numerical Simulation of 1-D debris flow (Kanako software) is used to simulate river conditions without and with sabo dam built. Simulation of debris flow refers to the flood incident on December 8, 2019 with a flow rate of 2.34 m^3s^{-1} obtained sediment at the bridge location reaching 1.5 meters. Sabo dam with a height of 14.5 meters is simulated using Q_2 (6.24 m^3s^{-1}) able to withstand the overall sediment deposition of 28,058 m^3, there is no deposition on the bridge. Simulation using Q_{100} (13.9 m^3s^{-1}), the sabo dam building retains 53,570 m^3 of sediment, but other than that, there is 7,756 m^3 sediment that still runs off downstream.

1. Introduction

The 7.4 magnitude earthquake on 28 September 2018 was caused by a shift in the Palu – Koro tectonic fault resulting in a tsunami, liquefaction and landslides in the Palu City, Sigi Regency and Donggala Regency areas. The impact of the earthquake in the form of a tsunami in Palu Bay, liquefaction in the Petobo Village, Balaroa Village, Sibalaya Village, Jonooge Village, and massive landslides occurred along the fault line of the Palu - Koro tectonic plate. One of the landslide locations is in Poi Village, Dolo District, Sigi Regency. After the earthquake, there have been two floods accompanied by debris flows. The first debris flow was reported on 29 June 2019, and the second occurred on December 8, 2019.

2. Literature review

2.1. Debris Flow

Debris flow is a flow of sediment and water mixture in a manner as if it was a flow of continuous fluid driven by gravity, and it attains large mobility from the enlarged void space saturated with water or slurry [1]. One of the parameters to determine debris flow criteria is a sediment concentration. Takahashi equation for equilibrium concentration of debris flow is described below [2]:

$$C_d = (\rho \tan\theta)/((\sigma - \rho)(\tan\phi - \tan\theta)) \quad (1)$$

where C_d is the sediment concentration, ρ is the mass density, θ is the slope of the river bed, σ is the mass density of bed material, and ϕ is the internal friction angle. The approximate value of C_d ranges $0.3 \leq Cd \leq 0.9C_*$, C_* is the sediment concentration by volume in movable bed layer (about 0.6). Internal friction angle ranges from 25° - 45° [3].

2.2. Governing equations

The basic equations used in the 1D debris flow simulation include momentum equations, continuity equations, river bed deformation which refer to several previous studies [2][4] [5].

Momentum equation:

$$\frac{\partial u}{\partial t} + \frac{\partial u}{\partial x} = g\sin\theta - \frac{\tau}{\rho h} \quad (2)$$

Continuation equation for the total debris flow volume:

$$\frac{\partial h}{\partial t} + u\frac{\partial uh}{\partial x} = i \quad (3)$$

Continuation equation for the material volume debris flow:

$$\frac{\partial Ch}{\partial t} + u\frac{\partial Cu}{\partial x} = i.C_* \quad (4)$$

Equation for determining change in bed surface elevation:

$$\frac{\partial z}{\partial t} + i = 0 \quad (5)$$

Sediment erosion/deposition velocity (i):

In case of erosion:

$$i = \delta_e \frac{(C_\infty - C)}{C_* - C_\infty}\frac{q}{d} \quad (6)$$

In case of deposition:

$$i = \delta_d \frac{(C_\infty - C)}{C_*}\frac{q}{d} \quad (7)$$

Riverbed shearing stresses:

$$\frac{\tau}{\rho h} = \frac{u\sqrt{(u^2+v^2)}\ d^2}{8h^3\left\{C+(1-C)\frac{\rho}{\sigma}\right\}\left\{\left(\frac{C_*}{C}\right)^{\frac{1}{3}}-1\right\}^2}\ ;\ \mathrm{C} \geq 0{,}4\,\mathrm{C}_* \quad (8)$$

$$\frac{\tau}{\rho h} = \frac{1}{0{,}49}\frac{u\sqrt{(u^2+v^2)}\,d^2}{h^3}\ ;\ 0{,}01 < \mathrm{C} < 0{,}4\,\mathrm{C}_* \quad (9)$$

$$\frac{\tau}{\rho h} = \frac{g\,n_m^2\,u\sqrt{(u^2+v^2)}}{h^{4/3}}\ ;\ C \leq 0{,}01 \text{ atau} \frac{\mathrm{h}}{\mathrm{d}} \geq 30 \quad (10)$$

For Eqs. (2)-(10) u (ms^{-1}) **is** flow velocity, x (m) is river horizontal distance, t is time, g (ms^{-2}) is the acceleration due to gravity, θ x is the flow surface gradients, τ is the riverbed shearing stresses, h (m) is the flow depth, ρ (kgm^{-3}) is the mass density of fluid phase, i is the sediment erosion/deposition velocity, C is sediment concentration by volume in debris flow, z (m) is the bed elevation, δ_e is the coefficient of erosion velocity, δ_d is the coefficient of deposition velocity, q is discharge of debris flow per unit width, d is mean particle size, C_∞ is equilibrium grain concentration, n_m is the Manning's roughness coefficient.

The parameters used in this software are mass density of bed material, mass density of a fluid phase, gravity acceleration, concentration of movable bed, concentration of material, Manning's roughness coefficient, coefficient of erosion rate, coefficient of accumulation rate, and diameter of material **[2]**.

3. Overview of the Study

Based on the JICA study (2019), estimated the volume of avalanches due to the earthquake in the river upstream Poi reached 5,200,000 m^3 with an area of 2.4 hectares slope of the river flow 14% - 28 %, it is feared if rain can cause potentially damaging debris flow infrastructure and community settlements located 1 Km downstream of the landslide.

Figure 1. Landslide in the upper Poi River due to earthquake. (source: River Basin Management of Sulawesi III)

In order to anticipate the recurrence of debris flow, in 2020 the Ministry of Public Works and Public (PUPR) through the River Basin Management of Sulawesi III (BWS Sulawesi III) in 2020 has built a closed type sabo dam, five units of dam consolidation (CD) and one bridge unit and normalization Poi River.

Table 1. Geometric data of the sabo dam and the consolidation dam of the Poi River

Construction	Height (m)	Overflow width (m)		Elevation (m)	Distance from upstream (m)
		Upper	Lower		
Sabo dam	14.5	15	10	131.95	500
CD 1	3	15	10	115.32	600
CD 2	5	15	10	104.62	650
CD 3	3	15	10	93.15	750
CD 4	3	15	10	82.47	850
CD 5	3	15	10	67.50	1,050
Dam bridge	-	-	-	59.50	1,300

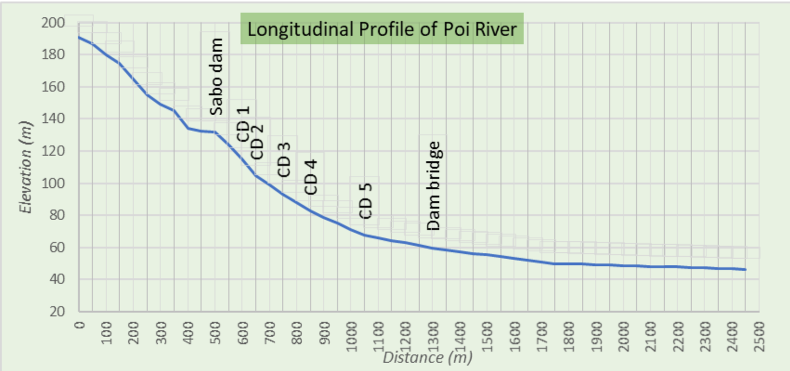

Figure 2. Longitudinal profile of Poi River

4. Research Method

In this study, the flood discharge that triggered the debris flow in 2019 was analyzed based on hourly rainfall data. Nakayasu's synthetic hydrograph method was used to supply a hydrograph for the upstream section. Flood discharge Q_2 and Q_{100} calculated from the maximum annual rainfall. Rainfall data used is the recording of rainfall at Station Sibalaya which is 5 km from the Poi River. Numerical simulation of 1D debris flow using Kanako software for river conditions without sabo dams based on flood discharge that occurred on December 8, 2019 and river conditions after the construction of the sabo dam with return period discharges Q_2 dan Q_{100}. The topographic data used is based on terrestrial measurements in 2020. The grain size parameter of coarse material is based on the interpretation of debris on December 8 2019, fine material using data from the grain size analysis of the Poi River bed in 2021.

5. Result and Discussion

5.1. Flood Discharge on June 29, 2019

Based on hourly rainfall records at Sibalaya, temporal rainfall with a total of 36 mm that occurred from June 28, 2019 at 18.00 to June 29 at 02.00 (8 hours) caused flooding accompanied by debris flow which was reported on June 29, 2019.

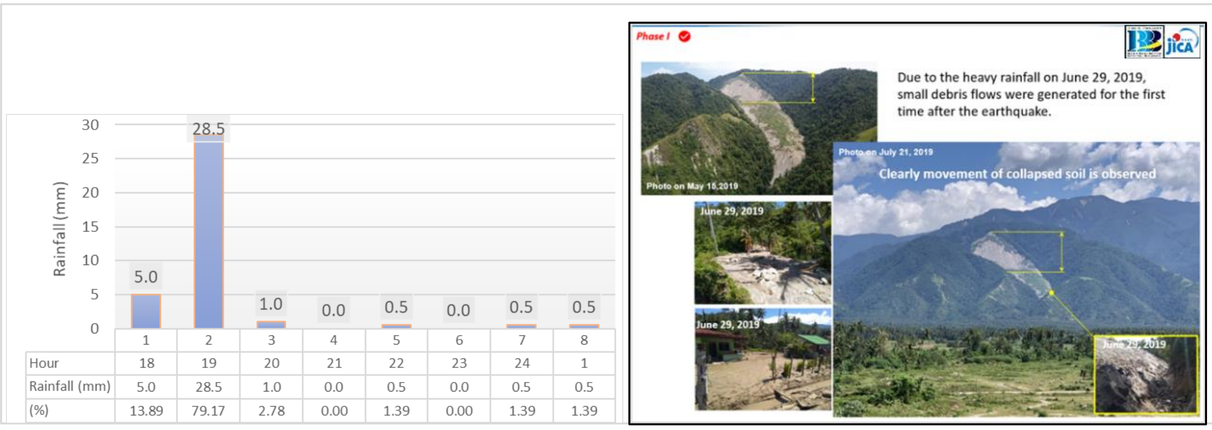

Figure 3. Rainfall graph (left), debris flow documentation 29 June 2019 (right). (source: River Basin Management of Sulawesi III)

5.2. Flood Discharge on December 8, 2019

Based on hourly rainfall records at Sibalaya, temporal rainfall with a total of 30 mm that occurred from December 7, 2019 at 21.00 to December 8 at 05.00 (8 hours) caused debris flow. Mud material mixed with boulders and wood covered the Palu – Bangga road with a height of 80 cm and a length of 200 meters. At least 5 houses were heavily damaged and 7 lightly damaged.

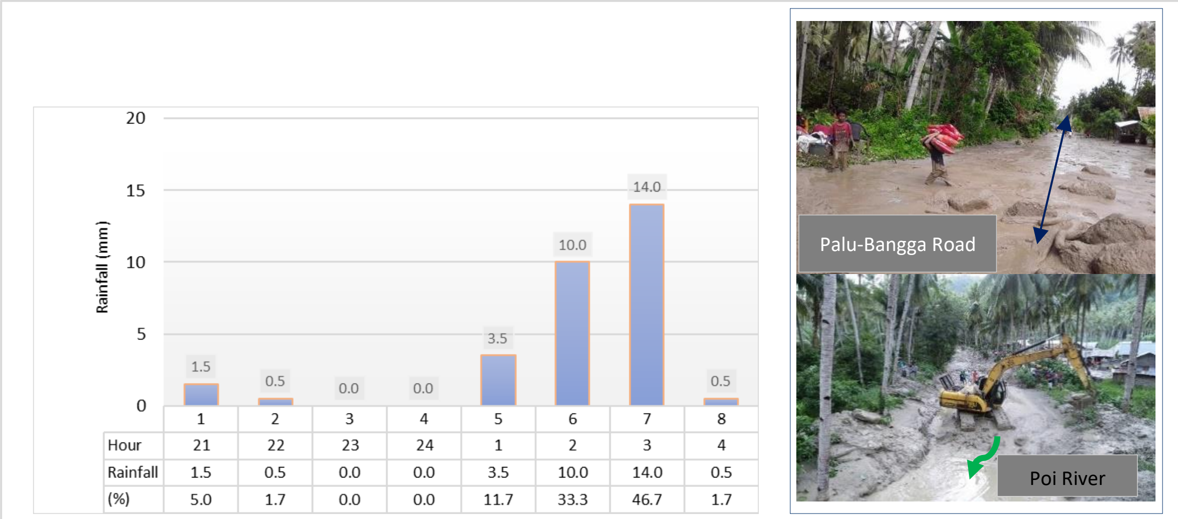

Figure 4. Rainfall graph (left), debris flow documentation 8 December 2019 (right). (source: River Basin Management of Sulawesi III)

Based on the rainfall data that caused the flood on December 8, 2019 (**Figure 4**) a flood discharge calculation was carried out using Nakayasu's synthetic hydrograph, the flood discharge (Q_p) = 1.29 m^3s^{-1}, and the flood hydrograph is shown in the following figure:

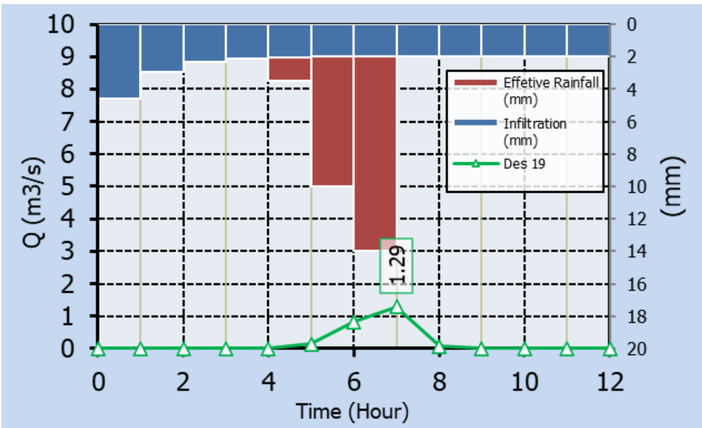

Figure 5. Flood hydrograph December 8, 2019

5.3. Flood discharge Q_2 dan Q_{100}

Maximum annual rainfall Sibalaya station with 18 years of observation (2003 – 2020) as follows:

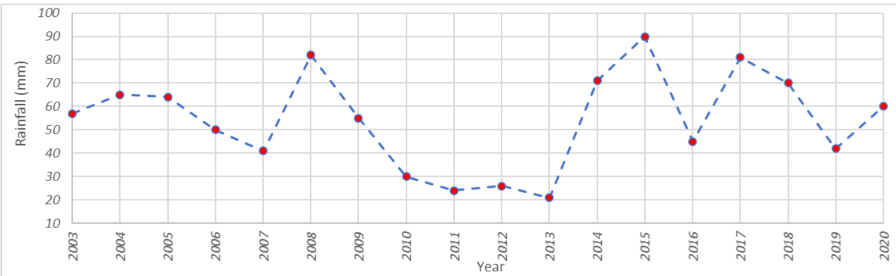

Figure 6. Graph of maximum annual rainfall Sibalaya station (source: River Basin Management of Sulawesi III)

By using Log-Pearson III frequency analysis, the rainfall frequency for the 2-year return period is 52.29 mm and the 100-year return period is 111.72 mm.

Table 2. Rainfall Frequency Analysis

Probability	Return Period	Log-Pearson III
		mm
0.5	2	52.29
0.01	100	111.72

Hydrograph flood discharge Q_2 and Q_{100} is calculated using the rainfall distribution Poi River in June 2019 (**Figure 3**), with the consideration that rainfall distribution resulted in a higher estimated flood discharge value than if using the December 2019 rainfall distribution.

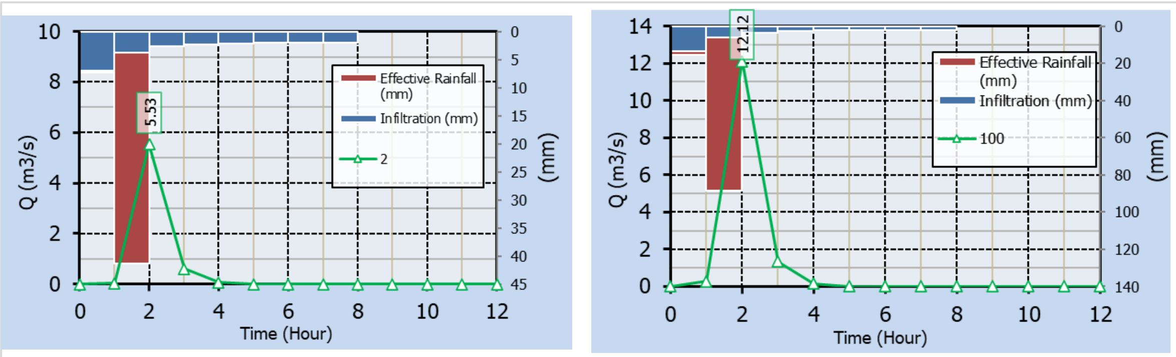

Figure 7. Flood hydrograph Q_2 (left) and Q_{100} (right)

5.4. Kanako's Debris Flow Simulation Parameters

The coarse grain diameter parameter used for the simulation of debris flow is estimated at an average of 0.3 m based on photos of documentation of debris flow events in the Poi River that occurred on December 8, 2019 (**Figure 4**). The results of the grain testing of the upstream of the Poi River (100 m upstream of the sabo dam) which was carried out in July 2021, obtained the value of d_{50} = 0.751 mm ≈ 0.002 m and σ =2,688 kgm^{-3}, so diameter fine grain diameter of 0.002 m is used.

For sediment concentration by volume in movable bed layer C_* = 0.6, mass density of bed material σ =2,688 kgm^{-3}, mass density of water ρ =1,200 kgm^{-3}, internal friction angle ϕ = tan 27° = 0.5 using the equation (1) the sediment concentration C_d = 0.52. Value of Manning's Coefficient is defined by the sediment transport condition classified by the volume concentration of flowing sediment *[6]*, for the value of C_d >0.2 used Manning's Coefficient 0.05. Value of coefficient for the erosion velocity δ_e is set to 0.007 and the deposition velocity δ_d is set to 0.05 *[6]*.

Table 3. Simulation parameters

Parameter		unit
Simulation time	25200 - 28800	s
Time interval of calculation	0.2	s
Diameter of coarse material	0.3	m
Diameter of fine material	0.002	m
Mass density of bed material	2,688	kgm^{-3}
Mass density of fluid (water and mud, silt) phase	1,200	kgm^{-3}
Concentration of movable bed	0.52	
Acceleration of gravity	9.8	ms^{-2}
Coefficient of erosion rate	0.007	
Coefficient of deposition rate	0.05	
Minimum flow depth	0.15	m
Manning's Coefficient	0.05	
Internal friction angle	0.5	
Number of calculation points	50	
Interval of calculation points	50	m

5.5. Simulation of Debris Flow Without Sabo Dam

Numerical simulation results of debris flow without sabo using a flood hydrograph on December 8, 2019 with peak discharge (Q_p) = 1.29 $m3s^{-1}$. At the upstream (sta 0 + 00 to sta 0 + 200) was eroded to a depth of 6.8 meters. On the part of the existing bridge (sta 1+150) deposition occurs as high as 1.5 meters. Downstream of the bridge there is deposition with a height of 0.2 to 0.9 meters. BWS Sulawesi III Palu records regarding the debris flow incident on December 8, 2019 stated that the sediment height reached 0.8 meters above the bridge.

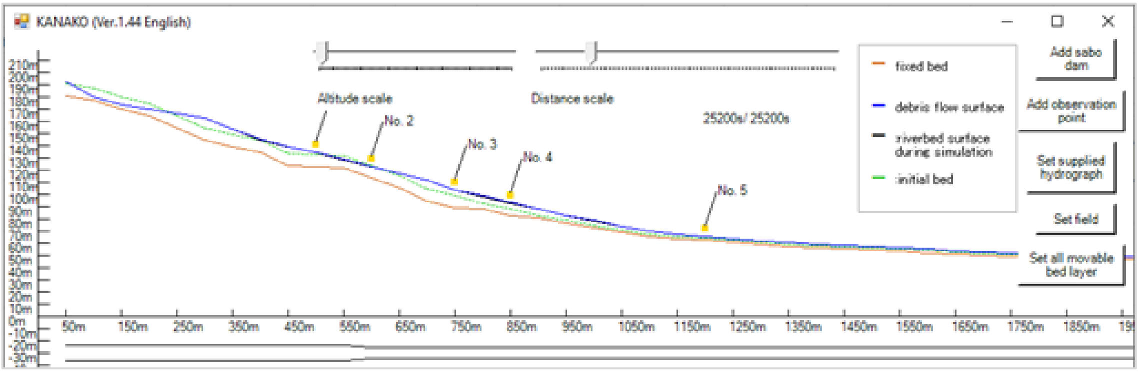

Figure 8. Kanako display of debris flow simulation results without sabo dam

The largest erosion volume of 4,437 m^3 occurred at sta 0+50, the total erosion volume was 14,405 m^3. The largest deposition volume of 4,826 m^3 occurred at sta 0+400, the total deposition volume was 43,503 m^3.

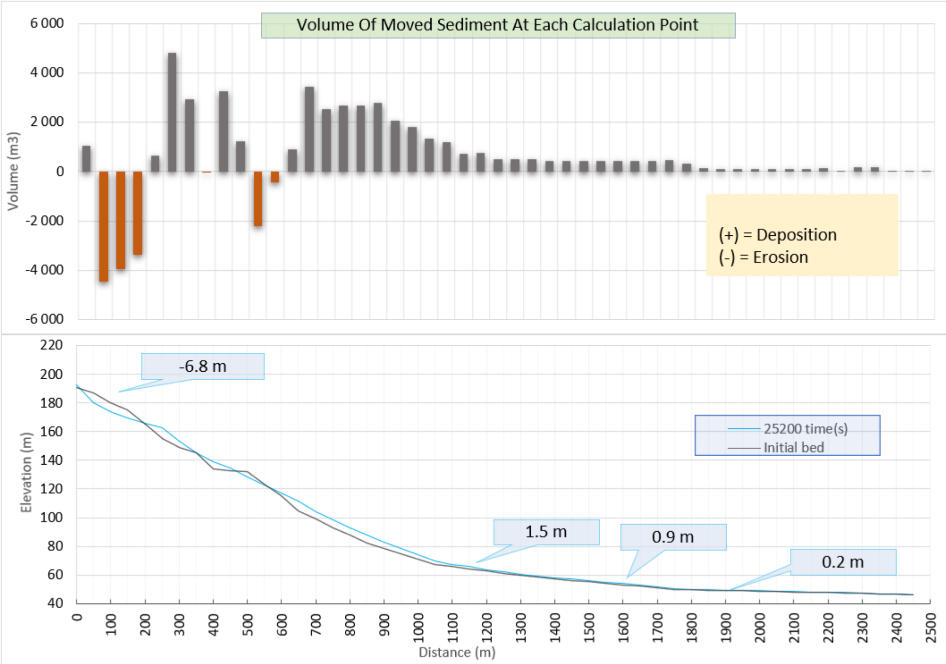

Figure 9. Volume of moved sediment at each calculation point (above), change in riverbed due to debris flow without sabo dam (below)

5.6. Simulation of Debris Flow With Sabo Dam

Numerical simulation results of debris flow with sabo using Q_2 (**Figure 7**), (Qp) = 5.53 m^3s^{-1}. At the upstream (sta 0+00 to sta 0+250) erosion occurred to a depth of 6.6 meters. Upstream of the sabo dam (sta 0+250 to sta 0+500) there was deposition with a height of up to 7.9 meters, still lower than the height of the sabo dam (14.5 meters). In the downstream part of the sabo dam there is no deposition, all sediment is retained in the sabo dam.

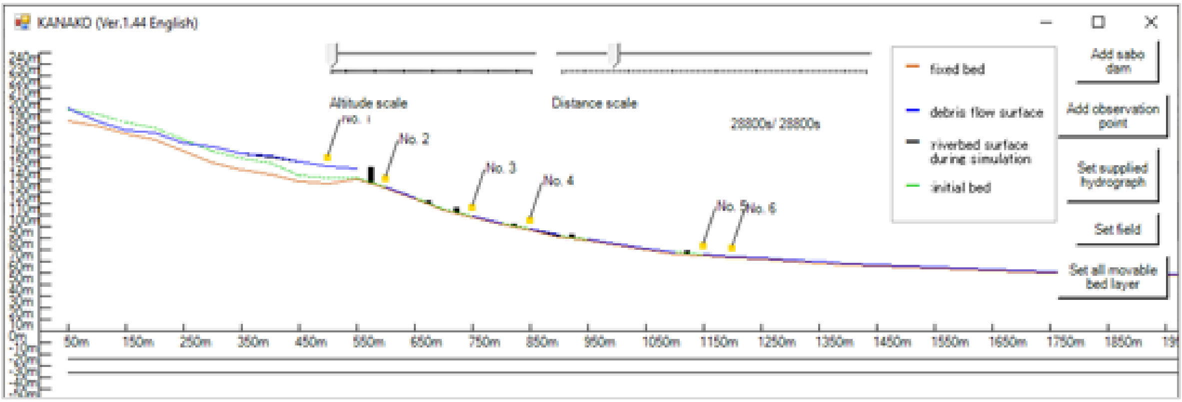

Figure 10. Kanako display of Q_2 debris flow simulation results with sabo dam

The largest erosion volume was 4,300 m^3 at sta 0+100, the total erosion volume was 13,058 m^3. The largest sediment deposition volume was 7,801 m^3 occurred at sta 0+400, the total sediment deposition volume was 28,058 m^3.

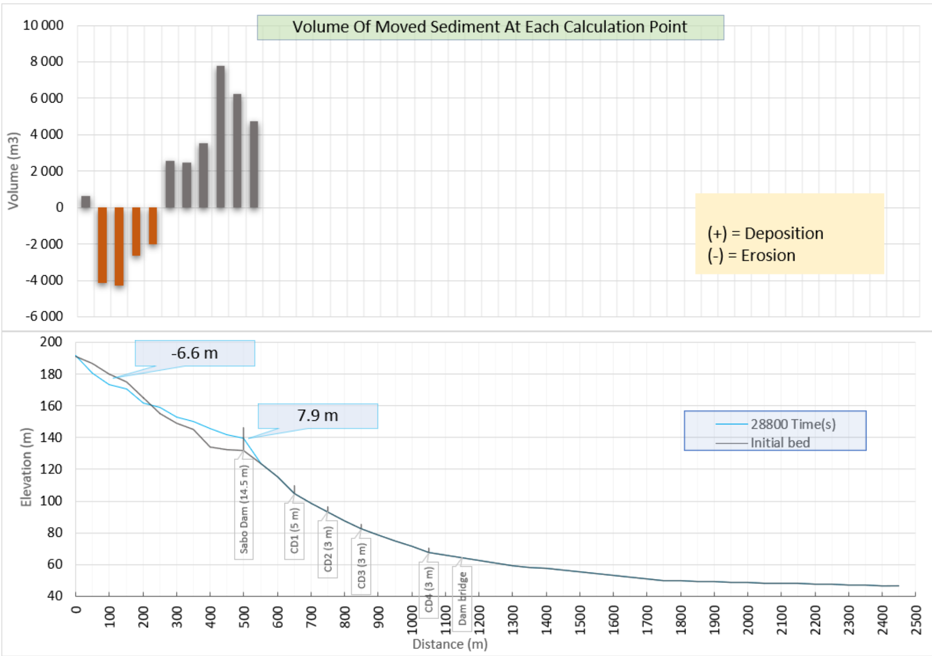

Figure 11. Volume of moved sediment at each calculation point (above), change in riverbed due to Q_2 debris flow with sabo dam (below)

Numerical simulation results of debris flow with sabo using Q_{100} (Figure 7), (Q_p) = 12.12 m^3s^{-1}. At the upstream (sta 0+50) there was erosion to a depth 4.6 meters. Upstream of the sabo dam (sta 0+200 to sta 0+500) there is deposition with a height of 11.7 meters. Between the sabo dam and CD 1 (sta 0+550) erosion occurred to a depth of 1 meter. At the location of CD 1 there was a deposition of up to 6 meters and it overflowed on top of CD 1 which was only 5 meters high. At the location of CD 2 it was deposited up to a height of 0.4 meters. Between CD 2 and CD 3 there was erosion to a depth of 0.3 meters. At the location of CD 3 sediments reached a height of 1.1 meters.

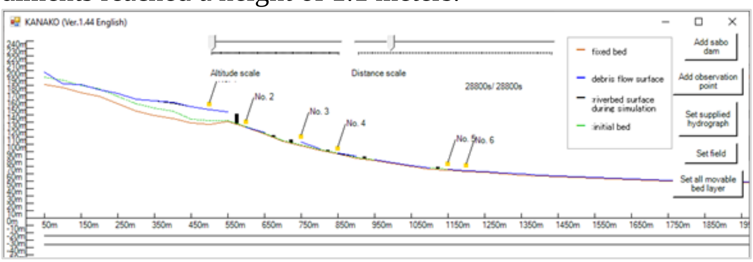

Figure 12. Kanako display of Q_{100} debris flow simulation results with sabo dam

The largest erosion volume was 2,993 m^3 at sta 0+50, the total erosion volume was 4,601 m^3. The sedimentation volume 11,101 m^3 occur in sta 0+400. The total volume of deposition is 61,326 m^3, the volume of sediment upstream of the sabo dam is 53,570 m^3, the volume of sediment that runs off downstream is 7,756 m^3.

6. Conclusions

a) Debris flow 29 June 2019 was triggered by 36 mm rainfall with a duration of 8 hours which occurred on 28 June 2019 at 18.00 to 29 June 2019 at 02.00.

b) The debris flow on June 29, 2019 was triggered by 30 mm of rainfall with a duration of 8 hours which occurred on December 7, 2019 at 21.00 to December 8, 2019 at 05.00.
c) Numerical simulation results of debris flow without sabo using a flood hydrograph on December 8, 2019 with peak discharge (Q_p) = 1.29 m^3s^{-1}, the total volume of erosion that occurred is 14,405 m^3, the deposition volume is 43,503 m^3.
d) Numerical simulation of debris flow Q_2 with sabo dam and dam consolidation shows that the sabo dam can hold all sediment up to a height of 7.9 meters in the sabo dam with a total sediment volume of 28,058 m^3.
e) Numerical simulation of debris flow Q_{100} shows that the sabo dam can hold up to 53,570 m^3 of sediment, but there is still a volume of 7,756 m^3 of sediment runoff downstream.

7. References

[1] T. Takahashi, Debris flow Mechanics, Prediction and Countermeasures, London: Taylor & Francis Group, 2007.

[2] A. Wisoyo, “The Analysis Of Sabo Dam Performance As A Sediment Control Structure In Putih River, Mt. Merapi,” *Civil Engineering Forum,* pp. 1271-1278, 2012.

[3] R. M. Iverson, “The Physics of Debris Flows,” *Reviews of Geophysics,* pp. 245-296, 1997.

[4] Sumaryono, K. Nakatani, Y. Satofuka and T. Mizuyama, “One-dimensional numerical simulation for sabo dam planning using Kanako (Ver. 1.40): A case study at Cipanas, Guntur Volcanoes, West Java, Indonesia,” *International Journal of Erosion Control Engineering, Vol. 2, No. 1,* pp. 22-32, 2009.

[5] K. Nakatani, T. Wada, Y. Satofuka and T. Mizuyama, "Development of Kanako, a wide use 1-D and 2-D debris flow simulator equipped with GUI," *WIT Transactions on Engineering Sciences, Vol 60,,* p. 49, 2008.

[6] Ministry of Public Works and Housing, Debris Flow Simulation For Review Master Plan Study, Jogjakarta: Ministry of Public Works and Housing, 2017.

Acknowledgments
Authors acknowledge the assistance of Water Resources Engineering and Management Study Program – Faculty of Civil and Environmental Engineering ITB and financial support from Ministry of Public Works and Housing.